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Random matrix theoretic approaches to sensor fusion for sensing and surveillance in highly cluttered environments

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14. ABSTRACT
Powerful algorithms that are able to detect, estimate, and classify increasingly weaker signals buried in noise are a critical technological component of several important US Air Force technologies such as SAR, MIMO radar and hyperspectral imaging among others. Advances in VLSI are making sensors cheaper and easier to deploy in increasing numbers. What limits our ability to detect and discriminate weaker statistical signatures from statistical clutter is not the sensor count but algorithm-independent statistical limits associated with the finite number of snapshots over which the effects of clutter can be averaged out. In the work supported by the Young Investigator Award, we have characterized the fundamental limits of statistical estimation and detection for a variety of problems of direct relevance to the US Air Force. These are organized into two thrusts:
Thrust 1: Characterization of fundamental limits and improved algorithms for detection, estimation and classification of matrix-valued signals buried in noise with missing data and,
Thrust 2: Characterization of fundamental limits of and improved algorithms for transmission of energy through highly scattering random media.

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In the work supported by the Young Investigator Award, we have characterized the fundamental limits of statistical estimation and detection for a variety of problems of direct relevance to the US Air Force. These are organized into two thrusts:
Thrust 1: Characterization of fundamental limits and improved algorithms for detection, estimation and classification of matrix-valued signals buried in noise with missing data and,
Thrust 2: Characterization of fundamental limits of and improved algorithms for transmission of energy through highly scattering random media.

We shall now highlight the successes achieved in the context of these thrusts.

Thrust 1: New algorithms and theory for detection and estimation of matrix-valued signals in noise

Impact: Outcomes of this research include precise quantification of the fundamental limits and associated performance guarantees for low-rank-signal matrix inference in the presence of a broad class of noise distributions that goes well beyond the standard Gaussian model and includes missing data settings. These insights have led to the development of new data-driven algorithms for low-rank matrix denoising that provably outperform PCA (or truncated SVD) based techniques and other convex relaxation based schemes.

Motivation: The truncated singular value decomposition (SVD) of the measurement matrix is the optimal solution to the representation problem of how to best *approximate* a noisy measurement matrix using a low-rank matrix. What we are really interested in practice is the (unobservable) denoising problem of how to best estimate a low-rank signal matrix buried in noise. Improving the low-rank signal estimate can yield improve estimates and classifier performance for all of the core Air Force sensing and sensing surveillance task that arise in radar, STAP, MIMO radar and hyperspectral imaging.

We have developed a **new algorithm** that exploits the PI’s results from random matrix theory to **improve denoising performance relative to the truncated SVD** in the moderate to low SNR regime. Our analysis reveals the fundamental limits of low-rank signal matrix extraction in the presence of noise and missing data.

Successes: The main contributions of this work are:

1) Our analysis shows that the optimal algorithm [1] should *shrink* the singular values of the data matrix in a Wiener-filter like manner so that larger singular values (corresponding to subspaces with higher SNR) are shrunk less than smaller singular values (corresponding to subspaces with lower SNR). The algorithm determines the shrinkage in an **entirely data-driven manner.** See Fig. 1 and Fig 2.

2) We show that the new algorithm [2] dramatically outperforms algorithms by Candes' and others [2,3] which utilize singular value thresholding including the setting where there are **missing or corrupted entries** as can happen for radar in cluttered environments. See Fig 3.

3) We prove that matrix regularization with **any convex penalty function** (such as the nuclear norm) will be suboptimal to the new algorithm we have developed. If the penalty function is designed to match the performance of our algorithm in the low SNR regime, then it will be suboptimal in the high SNR regime and vice versa; thus we will outperform convex regularization techniques and that too without introducing additional tuning parameters. See Fig. 3

4) A feature of our algorithm is that it can automatically **mitigate the effect of rank over-estimation**. This will greatly help stabilize the performance of Air Force sensing and surveillance systems (such as radar and STAP) which require adaptive estimates of subspaces whose ranks evolve with time (due to the complexity of the scene); see Fig. 4.

5) The analysis facilitates the precise characterization of Mean Squared Error (MSE) tracking performance for direction of arrival estimation in the presence of noise and missing data; see Fig. 5.

6) We have developed new algorithms for robust PCA that outperform state-of-the-art-algorithms based on the nuclear norm; see Fig. 6.

7) In collaboration with colleagues at AFRL, we have developed new eigen-analysis based algorithms for passive radar that can detect significant weaker signals than using classical correlation based techniques. See [6,7].

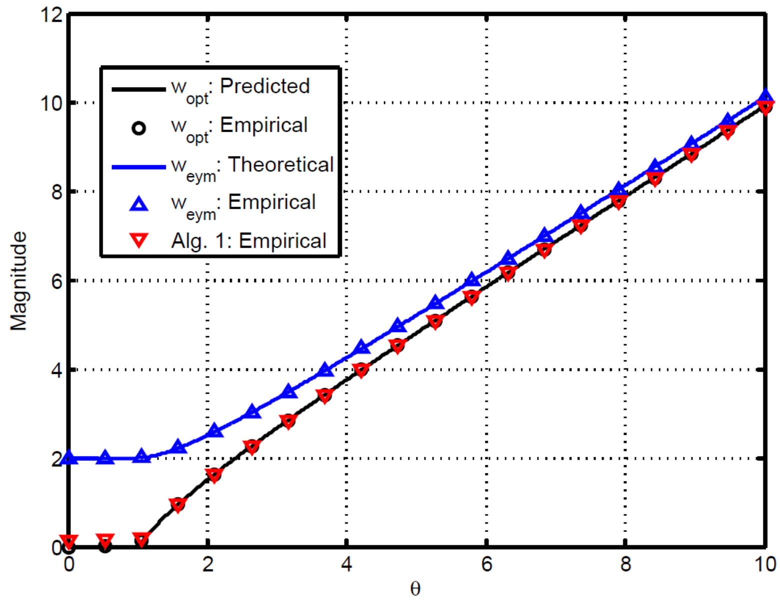


Fig. 1. The comparison of the weighting coefficient for the optimal new algorithm (Red Triangles) with that of the truncated SVD (blue line) as a function of the subspace SNR. We see the shrinkage effect where **higher SNR subspaces are shrunk less**. Note the thresholding effect where below a critical SNR we discard the subspace since it is "uninformative".

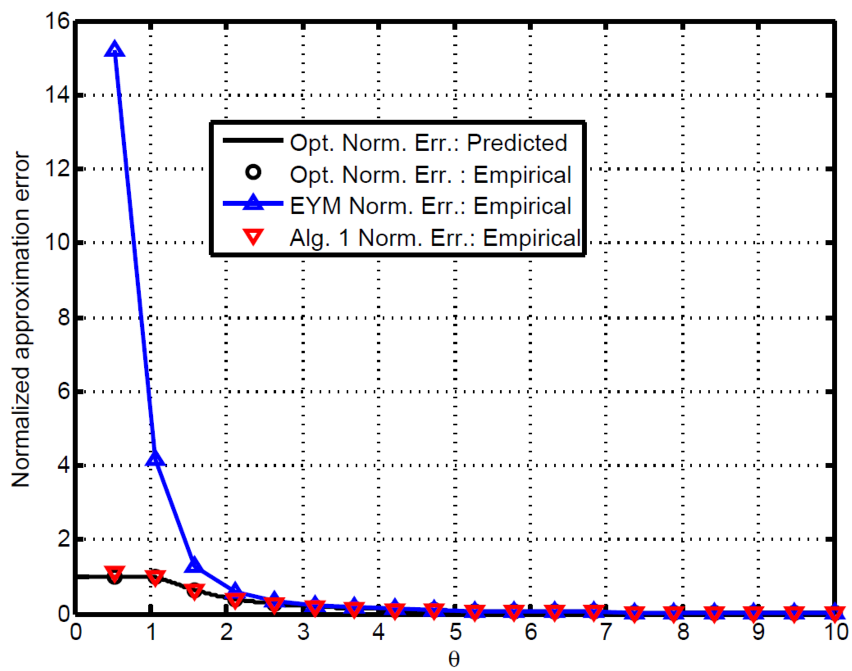


Fig. 2. Comparison of the denoising performance for the optimal new algorithm (Red Triangles) with that of the truncated SVD (blue line) as a function of the subspace SNR. We see that we improve get **dramatic gains in the low to moderate SNR regime**.

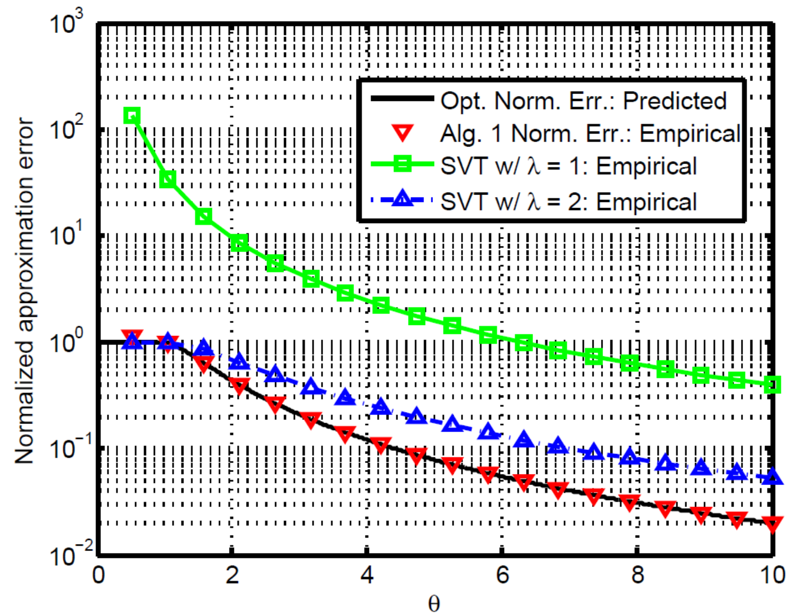


Fig. 3. Comparison of the denoising performance for the optimal new algorithm (Red Triangles) wit Candes' singular value thresholding (SVT) algorithm with two different tuning parameters as a function of the subspace SNR. We see that we get **dramatic gains in both low, medium and high SNR regimes**.

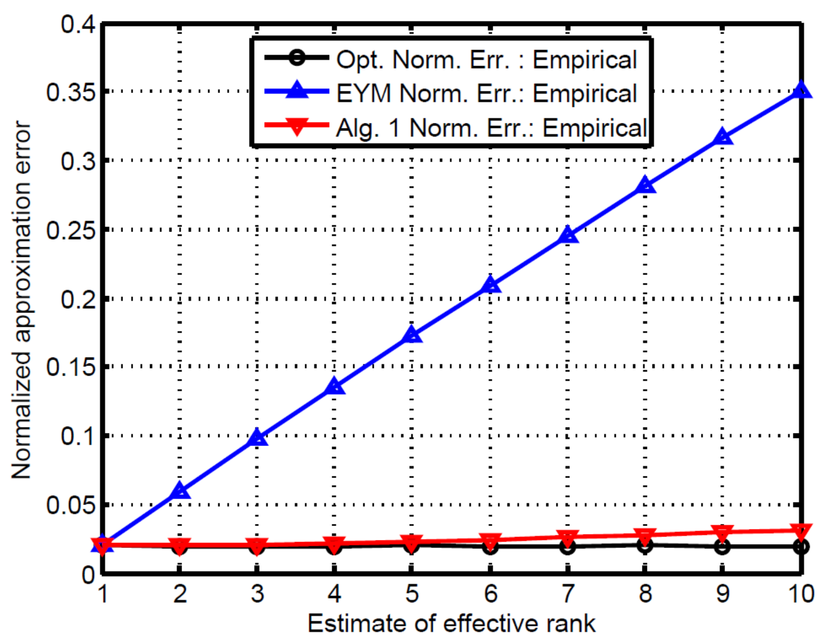
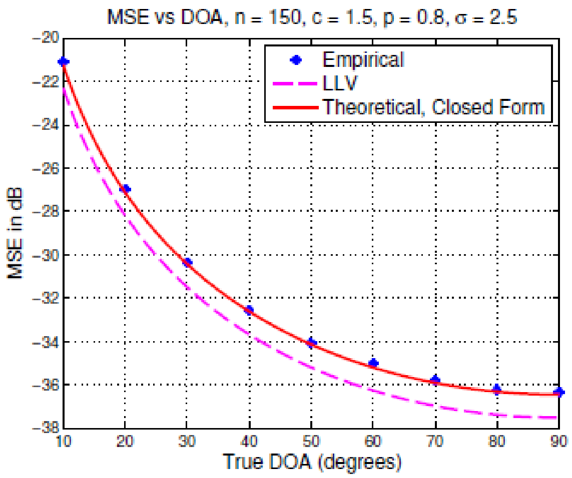
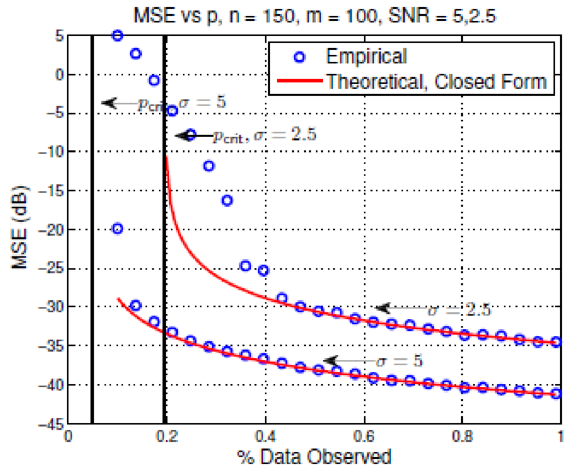


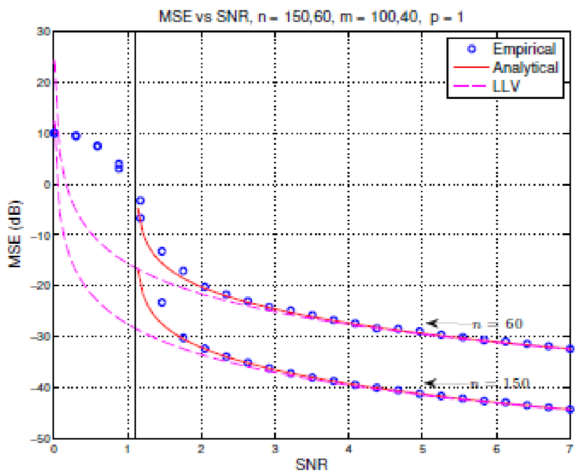
Fig. 4. Here we compare the denoising performance as function of the estimate of the rank. The plot shows that the new algorithm is able to mitigate the effect of rank overestimation better than the truncated SVD (in blue line).



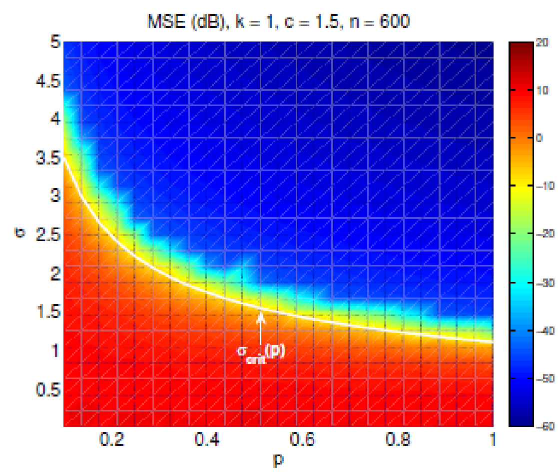
(a) MSE vs DOA.



(b) MSE vs p.

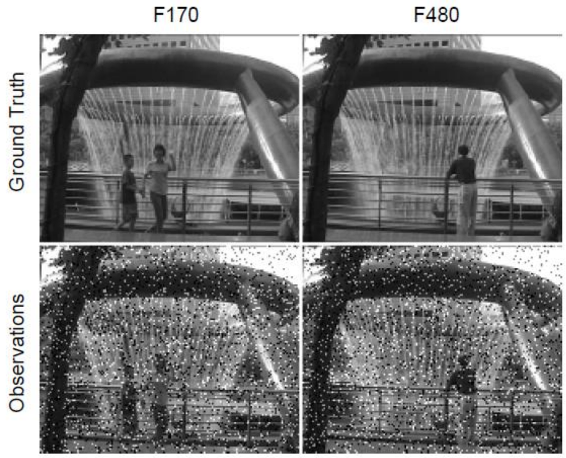


(c) MSE vs SNR.

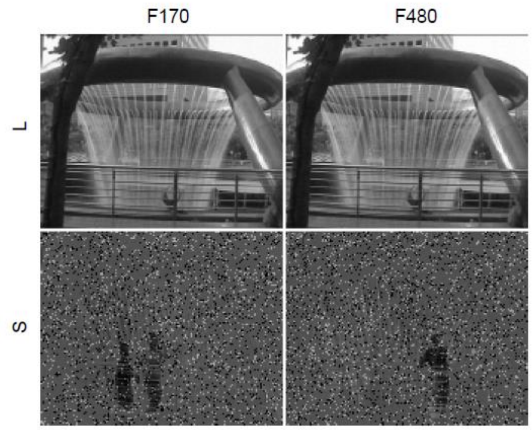


(d) MSE vs DOA.

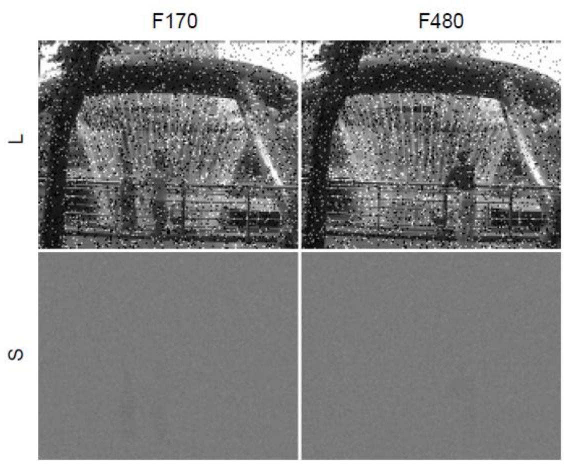
Fig. 5. MSE Performance of the MUSIC direction-of-arrival algorithm in the presence of noise and missing data. In (a)-(c) we compare the expression, derived in [4] with the expression in the literature. In (d), we derive a phase transition in system performance that separates a regime where the MUSIC algorithm reliably works from a regime where the MUSIC algorithm fails. The precise boundary of the phase transition depends in a simple manner on the number of sensors, number of snapshots, proportion of data observed as described in [4].



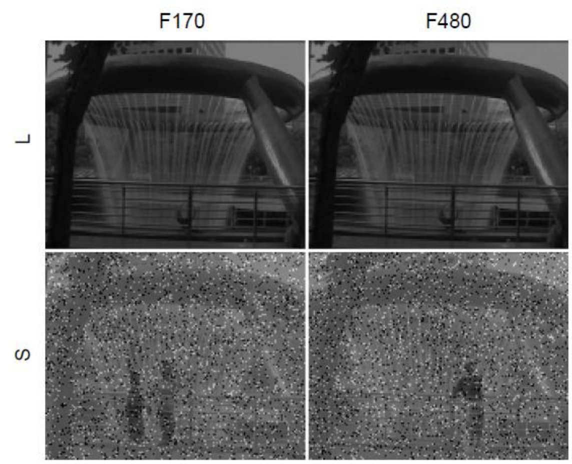
(a) Top: ground truth data, Y. Bottom: observed data, $\tilde{X}$.



(b) New algorithm (20) with $r = 1$ and $\lambda_S = 0.0035$. NRMSE = 9.5%.



(c) SVT-based updates (17) with $\lambda_L = 6.5$ and $\lambda_S = 0.0035$. NRMSE = 38.4%.



(d) SVT-based updates (17) with $\lambda_L = 300$ and $\lambda_S = 0.0035$. NRMSE = 42.3%.

Fig. 6. Performance of various algorithms for the background subtraction task. Upper right is the new algorithm described in [5]. The bottom two panels show the Robust PCA algorithm of [2] for two different choices of regularization parameter.

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Thrust 2: New algorithms and theory for increasing transmission through opaque random media

Motivation: Media such as glass and air are transparent because light propagates through them without being scattered or absorbed. In contrast, materials such as turbid water, clouds, fog and egg shells are opaque because the randomly arranged particles cause light to scatter in random directions, thereby hindering its passage. As the thickness of a slab of highly scattering random medium increases, this effect becomes more pronounced, and less and less of a normally incident light will be transmitted through, consequently limiting the use of optical techniques for sensing and surveillance in such media.

This is particularly pertinent to the Air Force because of the range of operating conditions encountered by airborne assets. In the past year, we have developed rigorous theory and algorithms that show that **orders of magnitude improvements in light transmission** can be achieved through such media. This can lead to new opportunities and sensing capabilities for the Air Force.

We have developed theoretical and experimental methods to increase the transmission of light by orders of magnitude through turbid random media that exploit the recent discovery of highly-transmitting eigen-wavefronts in a random medium [1-6]. We have developed general-purpose methods that can be used at optical, microwave and acoustic frequencies so that they can provide the foundation for broad new capabilities to the Air Force while enabling communication, sensing and imaging technologies for inhomogeneous media of all types.

Successes: We have made significant progress [7] in the theoretical and algorithm portions and thereby setting the stage for actual experiments. We summarize our successes:

1) We have numerically analyzed the phenomenon of the existence of highly transmitting eigen-wavefronts with fully spectral accurate simulators for 2D scattering systems as in Fig. 7 and have provided the first numerically rigorous confirmation of the bimodal shape of the transmission coefficient distribution (see Fig. 8) and the existence of an eigen-wavefront with transmission coefficient close to one for random media with a large number of scatterers.

2) We have developed iterative, physically realizable algorithms for transmission maximization that utilizes backscatter analysis to produce a highly transmitting wavefront in just a few iterations. See Fig. 9 for a comparison of normally incident and a highly transmitting eigen-wavefront and Fig. 10 for a convergence plot.

3) We have used and extended random theory to prove conditions under which perfect universal transmission is generically possible through such random media. See Fig. 11 and [9].

The development of an algorithm for increasing transmission using backscatter analysis is a significant accomplishment. Of particular importance is the fact that the algorithm constructs a highly transmitting eigen-wavefront in a handful of iterations – therefore it is possible to increase transmission by orders of magnitude in covert settings where it is not feasible to measure the transmitted wave and where the medium is dynamic but relatively stationary for tens of feedback cycles.

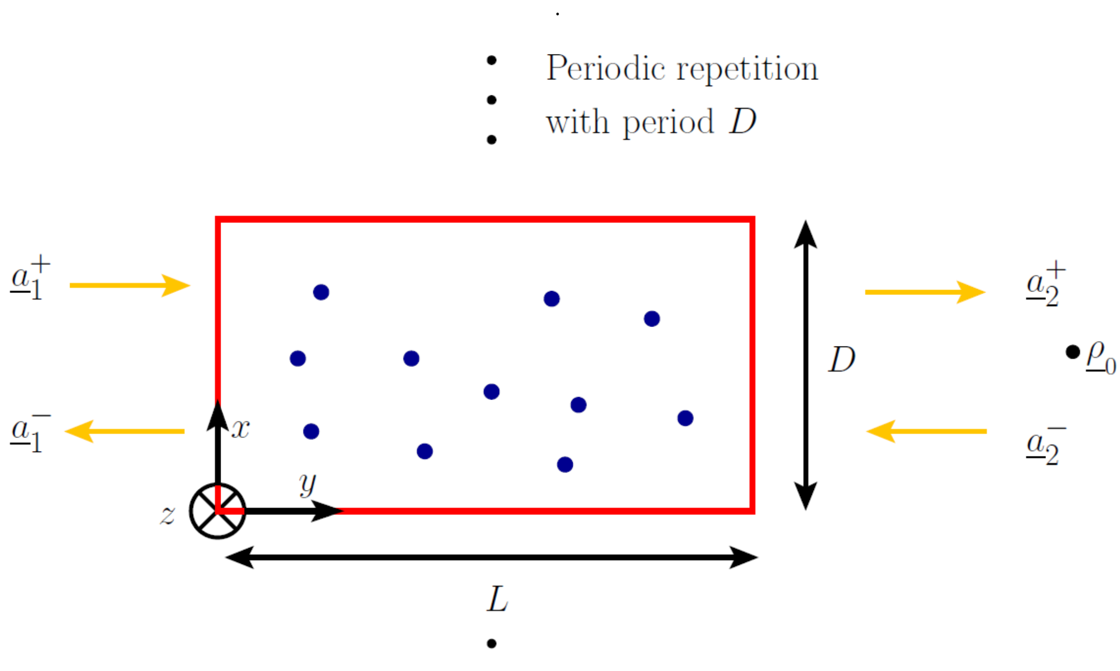


Fig. 7. Geometry of the scattering system considered.

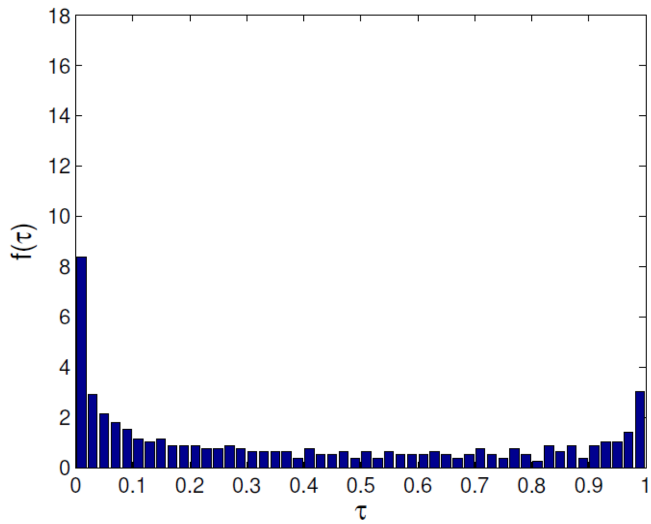
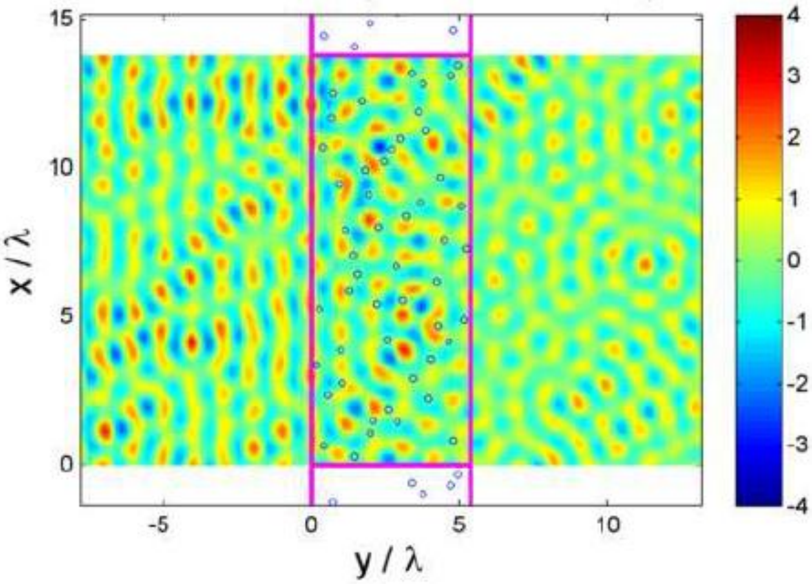
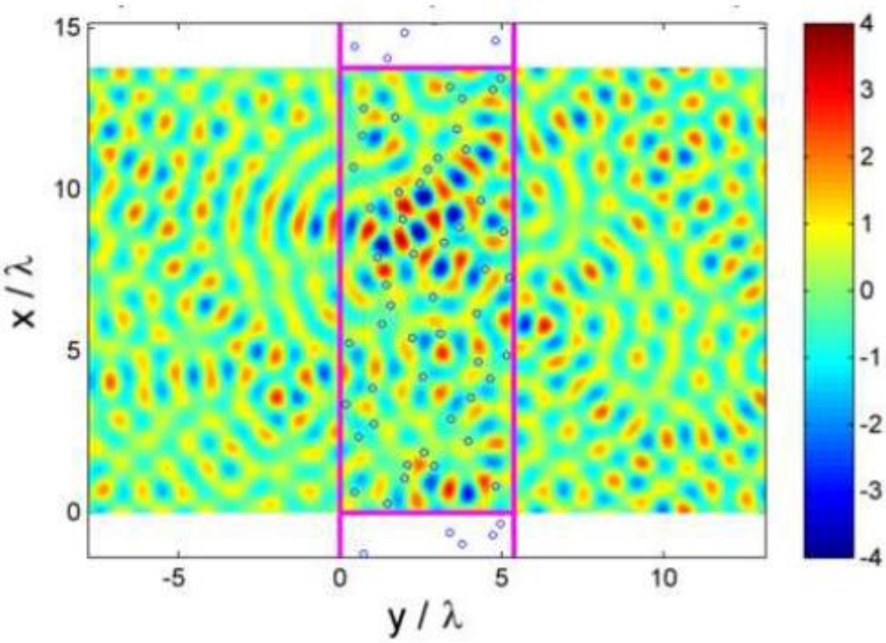


Fig.8. Empirical transmission coefficients distribution for the system in Fig. 2 with D = 197 λ, L = 1.2 x 10^4 λ with N = 14,000 randomly placed (non-overlapping) dielectric cylinders of radius 0.11 λ and refractive index 1.3. Here the mean inter-scatterer distance is about 6.7 λ. Note the <u>existence of many transmission coefficients close to one</u> even though the mean transmission coefficient is relatively small.



(a) Wavefield produced by a normally incident wavefront.



(b) Wavefield produced by the optimal wavefront.

Fig.9: Wavefield plot of the incident-plus-backscatter wave corresponding to (a) normally incident and the (b) optimal wavefront for the setup in in Fig. 1 with D = 14 λ, L = 5.4 λ and with 50 PEC cylinders with a radius of 0.11 λ and mean inter-cylinder distance of 0.8 λ. <u>The normally incident wavefront yields 50% transmission while the optimal wavefront yields 99.95 % transmission.</u>

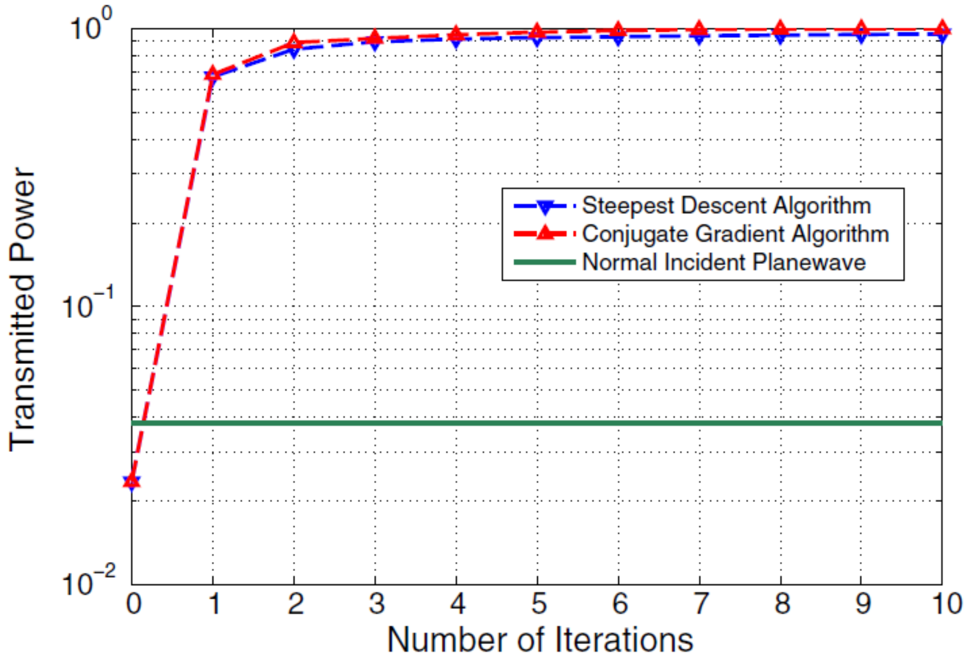
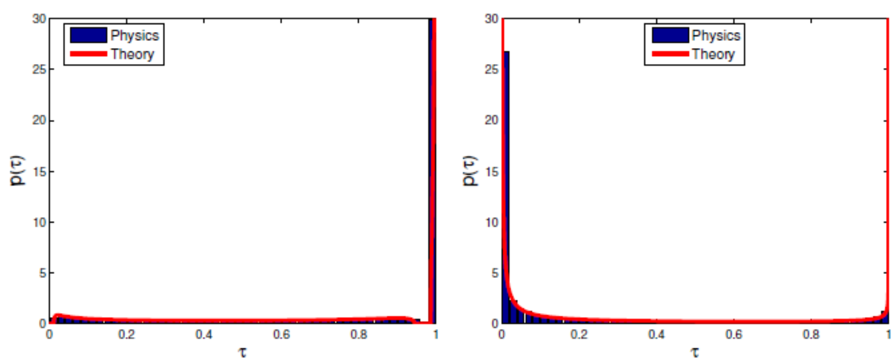


Fig.10: Transmitted power as a function of the number of iterations is shown for the new algorithms developed in [7]. Here, we placed 430,000 cylinders with refractive index 1.3 in the setup described in Fig. 1 and achieved a ***26x improvement*** in transmission relative to a normally incident wave. Note the rapid convergence of the algorithm.



(a) C=2. (b) C=33.

Fig. 11: The transmission coefficient distribution predicted by new theory versus numerically rigorous simulations. See [9].

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Changes in research objectives (if any):

N/A

Change in AFOSR Program Manager, if any:

Dr. Jon Sjogren was original PM.
Then PM was Dr. Tristan Nguyen and finally Dr. Arje Nachman.

Extensions granted or milestones slipped, if any:

N/A

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

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